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SOME CONSIDERATIONS CONCERNING THE ACCURACY OF POWER LEVEL CALCULATIONS IN THE CONTEXT OF THE CONTROL OF SS MATERIALS

by

K. B. Stewart

HANFORD LABORATORIES OPERATION
General Electric Company

March 11, 1960

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1.0 Introduction

A study of the accuracy of the power level calculations has been requested by personnel of the Plant and Industrial Engineering Operation. Some characteristics of this calculation can be adduced but the accuracy in the sense of freedom from bias leads to an impasse. It presumes that there is another measurement for comparison purposes for which there are engineering reasons to believe, the inherent error is smaller. For the power level values as calculated by the Foxboro Power Level Calculator no such measurement or calculation exists.

However, the calculations can be studied to determine whether it is worth-while to make further refinements relative to the various functions of the power level calculation. The accuracy requirements vary according to use where the most stringent requirements are in the control of SS Materials. An accuracy study in the context of SS Accountability needs should attempt to determine:

a. If increased accuracy in power level determinations will result in improved control of SS Materials. This entails a study of other sources of error and how these errors interact.

b. Whether it is possible to improve the accuracy in the power level calculations to a degree commensurate with the effort involved.

c. How, with affirmative answers to a and b, the accuracy can be increased.

2.0 Summary

It is doubtful whether any significant gains can be made in the control of SS Materials by a further refinement in the details of calculating power level values. The argument hinges on the following points.

a. The uncertainties associated with the prediction equations are quite large from the point of view of control of SS Materials.[1] Once a prediction equation has been adopted, any error in the constants induces a systematic error which will not cancel out in a percentagewise manner with increasing numbers of tube loadings.

b. The Foxboro Power Level Calculations may be biased, due to any of several possible reasons, but for a particular reactor there is a good deal of reproducibility in translating equivalent heat patterns into equivalent power level values.

c. There will be good control of SS Materials from the 100 Areas if there are no systematic errors in the estimated product yield values. This means that the prediction equations must be accurate relative to the estimated exposures rather than to the true exposures so that the product yield results become "calibrated" as it were, to the exposures by means of the prediction equations.

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[1] HW-31285, "Product Yield and Quality and U-235 Depletion in Irradiated Natural Uranium," R. O. Gumprecht, November 10, 1955 - Secret.

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3.0 Recommendations

a. Improvement in the conversion ratios is the most likely source of improvement in the control of SS Materials from the 100 Areas. Here the empirical approach of fitting product yield and observed exposures should be emphasized.

b. Thermal stratification in the effluent stream and/or heat loss in the downcomer are the most probable causes of inaccuracies in the power level calculations since little study has been made of this in recent years and since the other aspects are kept at relatively high levels of control and maintenance. It is doubtful whether further refinements here would have much effect on the accountability problem, but a study may be justified as an effort to bring all the aspects of the power level calculation up to the same levels of control and maintenance.

c. An electromechanical accumulator may be useful in integrating the power with respect to time. It could take the signals directly from the incremental temperature and flow sensing elements, and integrate these in such a manner as to give the total heat produced. Useful at first as a monitoring device, it may be found to have more general application.

4.0 Further Discussion

The control of SS Material from the reactors is based on a functional relationship between the Pu and the heat generated and creates a fairly elaborate accounting structure. The procedure is accomplished by:

a. obtaining a continuous record of the power level calculations,

b. integrating the power with respect to time to estimate the total heat produced,

c. apportioning the heat to the individual tubes where the heat is then converted into estimated exposure values, and

d. calculating the Pu density in the tube loading by a functional relationship between Pu density and exposure.

The power level determinations thus serve as a basis for a sequence of calculations ending in Pu density estimates for the individual tube loadings, and errors which arise in the power level calculations are perpetuated in the system. In the period of a month several thousand tube loadings are discharged and sent to be chemically processed. The 200 Area receipts in the case of Pu consist of the amount of Pu as estimated from the predicted yield values for the individual tube. The random errors which attach here tend to be eliminated in a percentagewise sense. For the random errors in a system to account for a 1% percentagewise error in the total Pu estimate of 2000 tube loadings, the errors for the individual tube loadings would have to be of the order of 40-50%.

The sum of the tube powers provides one basis of comparison for the reactor power as measured by the bulk outlet temperature method, although not that elusive "standard" with smaller inherent error. This comparison was studied with fairly extensive data available and the study leads to several interesting conclusions:

a. The over-all comparison for all 8 reactors based on 160 pairs of data indicates a discrepancy of 0.2% between the two methods.

b. The variation in this comparison between reactors is statistically significant. In other words, the direction that the comparison goes is not always the same for the different reactors.

c. The discrepancies between the two methods of estimating reactor power for the individual reactors are generally statistically significant.

d. Assuming that the sum of the tube powers is correct, the error in the over-all bias in the bulk-outlet temperature method for the sum of all 8 reactors is small compared to the possible errors in the prediction equations. (See appendix section 2.0)

5.0 Error Sources in the Accounting Structure

The power level value is calculated by the formula

$$P = kf(\Delta t) + A - B \qquad (1)$$

where

f is the flow rate in gallons/minute
Δt is the incremental temperature of the water in °C,
k is the constant which converts to KW or MW
A is the heat loss which is generated in the reactor which is not accounted for in the principal term in (1)
B is the heat induced in the system by friction.

Since the principal part of (1) tends to dominate the formula

$$\frac{dP}{P} = \frac{dk}{k} + \frac{df}{f} + \frac{d(\Delta t)}{\Delta t}$$

indicates that the percentagewise error in the equation is

% error in P = % error in k + % error in f + % error in Δt.

The value k = 0.2635 for conversion to KW was derived by taking into consideration the change in the specific heat of water as the water is heated in passing through the reactor. The constant was derived, however, when operating conditions were quite different from those that now exist. [2]

The flow rates are periodically checked by draw-down tests in all but the K Areas. The agreement is generally good considering the measurement error involved.

In the incremental temperatures the possible existence of thermal stratification is of concern. The error here would tend to be more of a sampling error than a measurement error since the thermohms are believed to be accurate. Other possible sources of error are

a. the power level calculator
b. heat loss in the downcomer
c. incorrect values for thermal shield and friction
d. inlet temperature
e. heat loss to the pad
f. heat loss due to vaporization
g. circulating gasses.

5.1 There may also be a systematic error introduced by the way the power level data are handled to estimate the total heat output. These may be due to

a. The method for estimating the area under the power level curve
b. Readings on the level set unit are taken at the power level setting. The deviations around the setting may not be random.

5.2 The heat allotted to an individual tube is determined by multiplying the total heat by a proportionality factor. Assuming that the total heat is correct, errors in the apportionment of the heat may be introduced by

a. incorrect header or tube pressure data
b. incorrect Δt data
c. calculating the proportionality factors at times which are not representative of the total period. (See Appendix, section 5.0)

5.3 For individual tube loadings the heat in terms of MWD is converted to the exposure in terms of MWD/ton. Then the Pu density estimate is based on an equation of the form

$$Y \frac{(\text{gms-Pu})}{\text{ton}} = aMe^{-bM}$$

where M is the exposure. Assuming that the exposure value is correct, errors may be introduced at this stage of the system by

a. errors in the constants a and b.
b. errors in the form of the prediction equation

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[2] 7-3738 "Numerical Evaluation of Operating Power," W. K. Woods, 3-27-46, Secret.

In general an $\epsilon\%$ error in a induces an $\epsilon\%$ bias in the prediction equations. With regard to b.), the correct form of the theoretical equation is

$$Y = aMe^{-bM} + \phi(M)$$

where $\phi(M)$ consists of an infinite series of terms similar in form to the principal part and which tend to be small for the usual range of M. In the equation for solid fuel element $\phi(M) = 0.015Y$ at 600 MWD/ton. $\phi(M)$ is an increasing function of M. While this error appears to be small it is, nevertheless, directional and its omission will introduce a bias. All this is by way of emphasizing the approximate character of the prediction equations. The empirical approach of fitting the constants from observed Pu density and exposure data will tend to mitigate these biasing effects.

6.0 Conclusions

It is well recognized that sources of error may exist in the calculation of power level values.[3] For instance, this is the motivation for the periodic draw-down tests. Thermal stratification in the effluent streams may exist and there are several tests which could be made to test this. However, it would be hard to justify such tests on the basis of possible improvements in the control of SS Materials because the experimentation would have to be extensive considering the number of reactors involved, and the gains in accuracy would have to be fairly striking in order to have much influence on the accounting structure.

The literature on the accuracy of the power level calculations is limited. Some earlier literature refers to tests done on the thermal stratification in the F reactor effluent stream, the accuracy of the Bailey Power Level Calculator and Recorder and draw-down tests in the H reactor. These studies antedate the installation and use of the Foxboro Power Calculators and reflect the conditions which existed at that time. This study was begun considering the accuracy of the power level calculation without reference to any function thereof, where the ideal answer would consist of confidence limits on the power level calculation with estimates of the random and systematic error components. These answers would then be useful in determining whether further refinements in calculating the power level values would be worthwhile. This type of approach is so difficult, however, that a more oblique approach is necessary, which accounts for the emphasis on the accuracies in the system in the context of SS Accountability needs.

The appendix contains discussions of the errors in the power level calculations and product yield predictions, comparisons of the sum of the tube and reactor powers and some ideas for testing for channeling in the effluent stream. The appendix was added to afford a more complete discussion and development of some of the topics.

K B Stewart

K. B. Stewart
Industrial Statistics
OPERATIONS RESEARCH & SYNTHESIS

[3] HW-56368, "Production Test IP-177A, Irradiation of Uranium to Improve Conversion Ratio Information," C. R. Richey, May 25, 1959. Secret.

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APPENDIX

1.0 Error Sources - A Statistical Treatment

The prediction equation for the Pu density for each fuel column is of the form

$$y_{ij} = a\, M_{ij}\, e^{-bM_{ij}} + \phi(M_{ij})$$

where

M_{ij} is the exposure in MWD/ton for the jth tube in the ith reactor

and

y_{ij} is the gms-Pu/ton units. Let

$$a = \hat{a}\,(1 + \epsilon_a)$$

$$b = \hat{b}\,(1 + \epsilon_b)$$

$$E_i = \hat{E}_i(1 + \epsilon_E)$$

$$f_{ij} = \hat{f}_{ij}\,(1 + \epsilon_f)$$

where

$\hat{a}$, $\hat{b}$, $\hat{E}_i$, and $\hat{f}_{ij}$

are respectively the estimates of the true values

a, b, E_i, and f_{ij}.

E_i refers to the heat produced in the time period under consideration and f_{ij} is the correct proportionality factor. Then the estimated Pu density is given by

$$\hat{y}_{ij} = aE_i f_{ij}(1 + \epsilon_a)(1 + \epsilon_E)(1 + \epsilon_f)\; e^{-bE_i f_{ij}(1 + \epsilon_b)(1 + \epsilon_E)(1 + \epsilon_f)} + \phi(M_{ij})$$

so that the ratio

$$\frac{\hat{y}_{ij}}{y_{ij}} \sim (1 + \epsilon_a)(1 + \epsilon_E)(1 + \epsilon_f)(1 - bM_{ij})\,(\epsilon_b + \epsilon_E + \epsilon_f)$$

$$\sim 1 + \epsilon_a + (1 - bM_{ij})(\epsilon_E + \epsilon_f) - bM_{ij}\epsilon_b \qquad (1)$$

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Example:

Let

E_i	= 200,000	$\hat{E}_i$	= 204,000	ϵ_E	= -0.026
f_{ij}	= (1.10)/2000	$\hat{f}_{ij}$	= (1.13)/2000	ϵ_f	= 0.075
e_{ij}	= 110 MWD	$\hat{e}_{ij}$	= 115.26	ϵ_M	= 0.020
M_{ij}	= 880 MWD/ton	M_{ij}	= 922.08	ϵ_a	= 0.027
a	= 1.0	$\hat{a}$	= 0.974		
b	= $+2.0 \times 10^{-4}$	$\hat{b}$	= $+2.15 \times 10^{-4}$		

so that

$$y_{ij} \quad 758.7, \ \hat{y}_{ij} = 757.1$$

and

$\hat{y}_{ij}/y_{ij} = .998 = (1.000 - 0.002)$. Upon substitution into (1) we obtain

$$R = (1 + 0.472(1 - 0.176) - 0.026 - 0.013) = 1.000.$$

in close agreement. If $\hat{a}$ had been 1.05 say, then

$$\hat{y} = 816.2$$

$$\hat{y}/y \sim 1.076.$$

Using formula (1) gives

$$\begin{aligned} R &= 1 + 0.0472(0.824) + 0.050 - 0.013 \\ &= 1.076 \end{aligned}$$

so that (1) affords a good model for studying the relative effects of errors in the values which are used in the prediction equations.

1.1 Errors in a, f_{ij}, and E_i.

It is apparent from equation (1) that percentagewise errors of a particular amount in the total heat produced in the reactor, in the tube factors, and in the constant a, will introduce percentagewise errors of approximately the same amount in the Pu density estimate for an individual tube column. (e.g., at 700 MWD/ton, 1 - bM = 0.85 for solid fuel elements so that percentagewise errors of e% in a, f and E, will introduce respectively percentagewise errors e%, 0.85e%, 0.85%e%). There are, however, important differences in the effects

of these errors, particularly from a long range point of view. The errors in the tube factors will tend to cancel out because of the constraint that the sum of the proportionality factors is forced to equal 1. Errors in $\hat{E}_i$ mean that there is a systematic contribution of error to all the tubes in the reactor for the time period under consideration. The long range effect of these errors depend on whether they vary for the different time periods and for the different reactors. Errors in $\hat{a}$, which is essentially the conversion ratio, are ultimately the most important because this error persists over tubes, times and reactors.

1.2 Errors in b.

A percentagewise error of e% say in the constant b, results in only a -bMe% error in the Pu density estimate. However, this error is directional. At 700 MWD/ton for solid fuel elements -bMe% = 0.15e%. The relatively small influence of small percentage errors in $\hat{b}$ is another argument for determining the equations empirically by concentrating most of the observed exposures at the upper and lower extremes of the exposure values which are experienced in practice.

1.3 There may be compensating biases in the system. In the example given $\hat{a}$ was assumed to be too small and $\hat{E}$ and $\hat{b}$ large, so that the resulting answer was fairly close. This is easily seen since

$$aMe^{-bM} = (a/k)M'e^{-(b/k)M'}$$

if M' = kM. Thus, good product yield estimates may be obtained where biases exist in exposure values provided the prediction equations are adjusted thereto.

1.4 Systematic errors in the flow rates and the incremental temperature values introduce errors of the same percentage in the heat produced. Thus, they introduce errors of about (1 - bM)e% in the product yield equations.

2.0 Reactor Power and the Sum of Tube Powers

Data are available which compare the sum of the unadjusted tube powers with the reactor power as calculated by the Foxboro Power Level Calculator. Here k is defined as

$$k = \frac{\text{the sum of the tube powers}}{\text{reactor power}}$$

and the following values are based on 16 or more observations obtained during the period from January 1958 to March 1959.

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Reactor	Average k	No. of Observations	$\frac{\bar{k} - 1.00}{s_{\bar{k}}} = t$
B	0.9942	24	-1.71
C	0.9829	21	-6.25
D	1.0168	18	6.30
DR	0.9804	22	-5.40
F	1.0255	16	17.00
H	0.9920	22	-4.04
KE	0.9915	20	-3.24
KW	0.9996	17	-0.16

If the sum of the unadjusted tube factors and reactor power levels are the same on the average, one would expect the average of the k factors divided by the standard deviation of the average k to be normally distributed with an average of 1. Then the probabilities that the absolute value of

$$t = \frac{\bar{k} - 1.00}{s_{\bar{k}}}$$

will exceed 1 and 2 are about 1/3 and 1/20 respectively, so that with the exception of reactors B and KW, the average k values are significantly different from 1.00. The data indicate that there is no general agreement between the different reactors as to the direction that the t value goes.

The main argument for using the sum of the individual tube powers as a comparison with the reactor power calculated by the bulk outlet temperature measurement is that there are a large number of measurements involved. If the errors in the tube powers were random and independent (which they are not) the percentagewise measurement standard deviations in the tube factors could be 40-45 times as large as the percentagewise measurement standard deviations in the bulk outlet calculations and still give as good results. It is difficult to say how much bias and error dependence exist among the estimate tube power values, but several conditions could be mentioned which would indicate their existence.

3.0 The Effects of Departures From a Cosine Flux Distribution

The product yield equations for a fuel column are weighted to adjust for the non-uniform flux distribution along a tube. This adjustment assumes a cosine distribution and entails a change in the value of b. For solid fuel elements the difference is

$$b_1 - b_2 = 0.24$$

where

b_1 is the adjusted value.

[redacted]

Since an error of e% in b amounts to an error of -bMe% in the product yield estimates it can be shown that in solid fuel elements at 500 MWD/ton a 1.3% error is introduced by assuming a uniform distribution of fluxes when the distribution is a cosine form and a -1.2% error is introduced by assuming that the distribution is cosine when it is actually of a uniform nature.

The following chart shows the error in assuming a cosine distribution when the curve is actually of the form given on graph 1. (Exposure 500 MWD/ton, solid fuel elements.)

Curve	form	error
1	cosine	0%
2	triangular	1.9%
3	triangular	1.9%
4	triangular	1.9%
5	$kxe^{0.1x}$	-0.2%
6	empirical	0.7%
7	uniform	-1.2%

From the appended curves it becomes apparent that

a.) peaking tends to make the product yield estimates too large

b.) flattening tends to make the product yield estimates too small

c.) translations of the peak along the tube axis have mild effects.

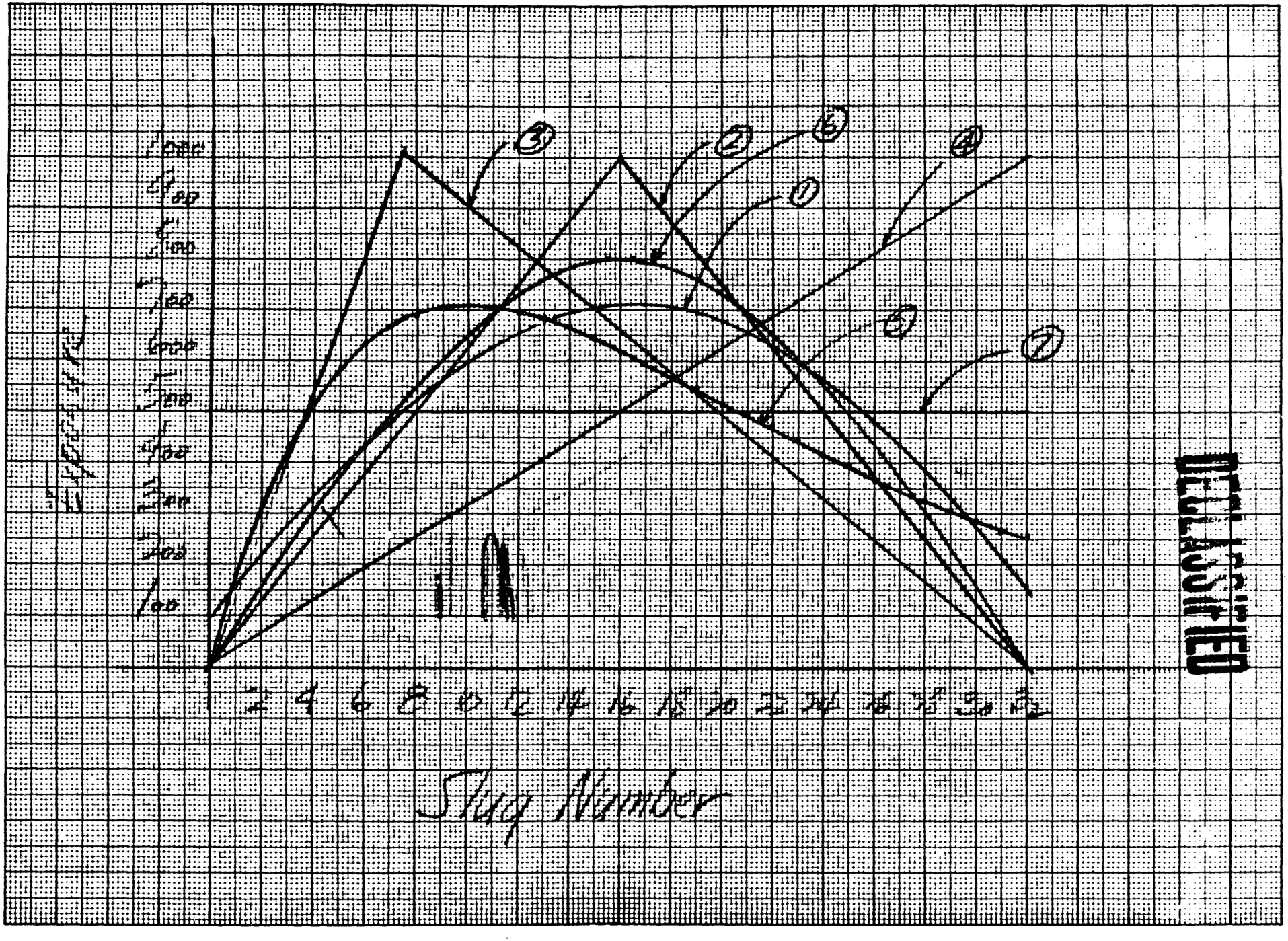
Further since the percentage error in the product yield estimates is roughly -bMe% the errors become larger at higher exposures. At 1000 MWD/ton these percentage errors are approximately double those given. Actually it is the frequency distributions of the exposures that are important in assessing the influence of these different flux distributions and in the cases of the triangular distribution all the cases given have the same frequency distribution of fluxes.

4.0 Evaluation of $\phi(M)$

The value $\phi(M)$ is relatively small for solid fuel elements at low exposures. However, the percentagewise error introduced by neglecting this term increases as the exposure increases. The following table gives the ratio of $\phi(M)$ to aMe^{-bM} for solid fuel elements.

M	$(\phi(M)/aMe^{-bM}) \times 100\%$
400 MWD/ton	0.7%
500	1.1%
600	1.5%
700	1.9%
800	2.3%
900	2.9%
1000	3.4%

[redacted]



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Since this ratio is approximately linear within the range of exposures usually experienced, the average percentagewise contribution by this part of the prediction equation is the ratio corresponding to the average exposure. If, for example, the average exposure is 700 MWD/ton the average ratio would be 1.9%. Suppose that the prediction equation and average exposures are correct on the average. Then neglecting the second term in the series would result in a 1.9% bias.

5.0 An Aspect of Tube Factor Error

Errors may exist in the tube factors due to incorrect flow or incremental temperature measurements. Another error may be introduced by computing the factors at times which are not representative of the total time period. Some data were gathered, mostly in connection with the problem of whether tube factors should be calculated for short operating periods. The following conclusions were based on these data.

a.) The variability in the factors is greatest during the period of startup, but the effect of this variability is small because power is also smallest during this period.

b.) After equilibrium is reached the variation in the factors is relatively small.

c.) It is not necessary to determine the tube factors a large number of times provided there is good knowledge of when the reactor is in equilibrium, when it is a state of transition, and when the periods of equilibrium start and end.

6.0 Testing for Thermal Stratification

The incremental temperature is equal to

$$\Delta T = T_o - T_i$$

where

T_o and T_i are the outlet and inlet temperatures. The errors in these values may be broken down into measurement and sampling components, and the main point of concern in these measurements is with sampling error in the outlet measurement due to thermal stratification and/or heat loss in the downcomer. That is to say, the measurement errors are believed to be negligible because the thermohms measure accurately enough the temperatures that they do measure but that these temperatures may be in error because they do not give a correct picture of the average heat of the water just as it leaves the reactor. There are several possible ways of checking for thermal stratification.

a.) Thermohms may be placed at different positions in a cross section of the outlet stream. Then the different measurements made at the same time would indicate whether stratification exists.

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b.) An additional thermohm may be established at a point which is far enough downstream to insure that mixing has occurred. Comparing measurements here with the regular outlet temperature measurements may help to establish whether stratification exists.

c.) If the power of the reactor is held constant, but the flux distributions throughout the reactor are varied, stratification effects should show up in the outlet temperature measurement. A measurement point downstream would be needed to check on whether the power has been held constant. This way is probably very difficult to carry out.

An approximate method of estimating the heat loss in the downcomer would be by determining the heat loss per unit length in the outlet stream for a given flow rate. Then by calculating the amount of water which has left the reactor but which has not reached the measurement point, the heat loss could be estimated in a rough way. It may be possible to estimate the heat losses from purely theoretical considerations. At any rate, no allowances for heat losses in the downcomer are made at the present time.

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